

## Processing GPS Data from Travel Surveys

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### 1 Introduction

Interest in using Global Positioning System (GPS) technology in transport research has grown considerably in recent years (Quiroga, 2000; Wee et al., 2002; Baffour, 2002; Ranjitkar et al., 2002; Stopher et al., 2002; Li et al., 2004). In particular, there has been a substantial interest in using GPS in conjunction with household travel surveys (HTSs), as a means to investigate and correct deficiencies in the ability of respondents to identify precise geographic locations, routes, and times of travel (Wolf et al., 2000; Wagner, 1997; Wagner et al., 1998; Draijer et al., 2000). While GPS can provide highly accurate spatial and temporal data on travel activity, the benefits of the technology cannot be fully realised without overcoming some significant hurdles relating to reducing the magnitude of the data problem. The data collection capabilities of GPS are, for all intents and purposes, unlimited. Off the shelf GPS data logging equipment commonly used in transport research can record hundreds of thousands of track points in the space of a few days. While it is relatively straightforward to import and view GPS data in most standard Geographic Information System (GIS) packages, it is extremely time consuming, if not impossible, to conduct any kind of meaningful data analysis using standard program tools for displaying and editing data, and running location and attribute queries.

The management, manipulation, and analysis of GPS data, therefore, require the development of specialised computer software applications. This paper describes four customised software applications developed to process, correct, and analyse in-vehicle and wearable GPS data collected as part of a HTS in Sydney, Australia. The first application separates continuous streams of GPS records into days and then into trip based data for visualisation and analysis. The second application corrects GPS data for "cold start" problems, in which some significant amount of travel may be completed before records of time and position begin to be stored. The third corrects for data losses within "urban canyons". The paper details the rules used in the applications, and the techniques used for managing and storing the resulting output data. Following that we also describe procedures that we are now implementing to automatically detect the mode used with a wearable device, and the purpose of the trip.

The Institute of Transport and Logistics Studies at the University of Sydney (ITLS) has been working on these issues for some time, and has developed a number of rules and algorithms for handling GPS data collected from household travel surveys (Stopher et al. 2002, 2003), and a variety of travel time studies (Bullock et al., 2003; Bullock and Jiang, 2003). The context within which this has been done is that the GIS software of choice is TransCAD® and most programming has been undertaken in the developer's tools of TransCAD® – GISDK®. Some of the steps undertaken are specific to the requirements of TransCAD®, while most steps would be equally necessary for any GIS software. Similarly, the equipment that has been used by ITLS to collect GPS data is the in-vehicle and wearable GeoLogger® developed by GeoStats, which uses a Garmin GPS receiver, now being replaced by the Neve StepLogger which uses a uBlox antenna/receiver and custom circuitry for processing and storing (Stopher et al., 2005).

## 2 Applications

### 2.1 Application 1: Converting Continuous GPS Data into Trip Based Records

#### 2.1.1 Re-formatting the Data

Most GPS receivers provide output information in a format known as NMEA 0183, which is a standard developed by the National Marine Electronics Association to define electrical signal requirements, data transmission protocol and timing, and specific sentence formats, and allow data communication between GPS equipment/instruments (Wolf, 2003). Under the NMEA format, data are transmitted in the form of coded 'sentences.' There are a number of different sentence types (e.g., RMC, GGA, GSA, GSV) that can be transmitted within the NMEA format, and these determine what information a GPS receiver will output (Wolf, 2003). GPS receivers connected to data logging equipment used in transport research commonly provide 10 to 12 main variables. Both the GeoLogger and the StepLogger output the same information.

First, there is usually a code that indicates if the current record is a valid record, or if it represents the restarting of recording data, after a series of one or more invalid data points. Latitude and longitude are provided, in a format that represents either degrees, minutes and decimal minutes, or in degrees and decimal degrees. In the case of the GeoLogger, the latitude and longitude are also accompanied by a compass point that indicates the appropriate hemisphere of the position. Next in order is usually the time and date at which each record was obtained. These are provided in Universal Coordinated Time (UTC), which will usually be significantly different from the local time and date. The next two standard items are the speed, determined from Doppler measurement, and the heading. Three additional items may optionally be provided, depending on hardware and software configurations of the equipment. These are the altitude (in metres above sea level), the Horizontal Dilution of Precision (HDOP) which measures how the satellites are arranged in the sky at the time of the record, and the number of satellites in view. Examples of the full standard download from the GeoLogger is provided in Figure 1 and the StepLogger in Figure 2.

**Figure 1:** Example Output from the GeoLogger

VALI D	LATITUDE	HEMI- SPHERE	LONGITUDE	HEMI- SPHERE	UTC TIME	UTC DATE	SPEED (KPH)	HEAD- ING	ALTI- TUDE	HDOP	SATEL- LITES
V	33.89243	S	151.19162	E	50655	190202	0	0	43	2.4	3
A	33.89237	S	151.19165	E	50658	190202	20	23	43	2.4	3
V	33.89205	S	151.19153	E	50703	190202	0	0	43	2.4	0
A	33.8916	S	151.19128	E	50708	190202	40.2	340	43	2.4	3
V	33.89112	S	151.19105	E	50713	190202	0	0	43	2.4	0
A	33.89077	S	151.19088	E	50718	190202	28	324	43	2.4	3
A	33.8904	S	151.1906	E	50723	190202	35.4	327	43	2.4	3
A	33.88993	S	151.19023	E	50728	190202	45.9	326	43	2.4	3
A	33.88963	S	151.19005	E	50733	190202	19.3	351	43	2.4	3
A	33.8893	S	151.19028	E	50738	190202	39.9	41	44	2.4	4
A	33.88895	S	151.1908	E	50743	190202	45.9	53	42	2.4	4
A	33.88863	S	151.1914	E	50748	190202	45.2	58	42	2.4	4
A	33.88832	S	151.19198	E	50753	190202	45.5	57	43	2.4	4
A	33.88797	S	151.19262	E	50758	190202	55.3	51	43	2.4	4
A	33.88747	S	151.19325	E	50803	190202	57.9	43	42	2.2	4

**Figure 2:** Example Output from the StepLogger

Figure 2. Example output from the StopLogger.

Valid	Date	Loc Time	Longitude	Latitude	Altitude	Heading	Speed	Satellites	HDOP	
A	23/04/2005	0:56:50	138.6184	-34.80916	-3	145		1	5	2.3
A	23/04/2005	0:56:56	138.6184	-34.80916	1	8		1	6	2
A	23/04/2005	0:57:07	138.6184	-34.80909	5	80		1	6	1.5
A	23/04/2005	0:57:08	138.6184	-34.80908	5	316		1	5	2.2
A	23/04/2005	0:57:12	138.6184	-34.80908	6	118		1	6	2
A	23/04/2005	0:57:13	138.6184	-34.80908	6	106		2	6	2
A	23/04/2005	0:57:14	138.6184	-34.80908	7	90		4	6	2
A	23/04/2005	0:57:15	138.6185	-34.80908	7	90		4	6	2
A	23/04/2005	0:57:16	138.6185	-34.80908	8	92		4	6	1.6
A	23/04/2005	0:57:17	138.6185	-34.80908	8	95		4	6	2
A	23/04/2005	0:57:18	138.6185	-34.80909	9	92		5	5	1.6
A	23/04/2005	0:57:19	138.6185	-34.80909	9	86		5	8	1
A	23/04/2005	0:57:20	138.6185	-34.80908	9	87		5	5	1.9
A	23/04/2005	0:57:21	138.6186	-34.80908	8	99		6	6	1.4
A	23/04/2005	0:57:22	138.6186	-34.80908	8	103		6	8	1
A	23/04/2005	0:57:23	138.6186	-34.80909	8	92		5	5	2.2
A	23/04/2005	0:57:24	138.6186	-34.8091	7	93		4	6	2
A	23/04/2005	0:57:25	138.6186	-34.8091	7	98		5	5	1.9
A	23/04/2005	0:57:26	138.6187	-34.80911	7	102		5	8	1
A	23/04/2005	0:57:27	138.6187	-34.80911	8	100		6	8	1
A	23/04/2005	0:57:28	138.6187	-34.80912	8	92		5	6	2
A	23/04/2005	0:57:29	138.6187	-34.80912	8	97		5	6	2
A	23/04/2005	0:57:30	138.6187	-34.80912	8	94		5	7	1.3
A	23/04/2005	0:57:31	138.6188	-34.80913	8	93		5	5	3
A	23/04/2005	0:57:32	138.6188	-34.80913	8	89		5	5	1.6

The HDOP and number of satellites in view are important measures that determine the quality of the record. For a correct position fix, there must be a minimum of four satellites in view, because there are four equations with four unknowns to be solved to determine position. Any observation with fewer than four satellites in view must be considered suspect. The requirement of four satellites is used to solve the 3D and time shift. If we fix the altitude, only 2D and time need to be estimated. In this situation, we still can obtain the correct location using the three satellites only. From Figure 1, the Valid status is still 'A', even though the number of satellites was three. The GPS receiver has applied this procedure, and is the reason that observations with three satellites in view are indicated as valid. Any observation with six or more satellites in view should give position information of sufficient accuracy for applications examining travel behaviour. HDOP determines how the satellites are dispersed. If all satellites are along the horizon, or they are lined up immediately above the receiver, then the accuracy of the position is again questionable, irrespective of how many satellites are in view. Either of these situations would result in a high value of the HDOP, which indicates a probably poor quality record. Low values of HDOP indicate that the satellites are widely dispersed, so that the position information should be much more accurate.

As can be seen in Figure 1, there are initial problems shown here in positioning, because three or fewer satellites are in view, although they are reasonably well dispersed, as is shown by the HDOP value of 2.4. Ideal values would be an HDOP of less than three and more than four satellites. The record in Figure 1 was obtained at the beginning of a trip, and the drop outs of records are quite typical of what happens as the GPS device attempts to acquire position. It can be seen here that the receiver took about 43 seconds (from 5:06:55 to 5:07:38) to acquire a fourth satellite and start to produce reliable data. The speeds and headings shown in the first nine records can be considered to be highly unreliable, and probably of no use. It is worth noting that such problems may occur not only during signal acquisition, as shown by Figure 1, but at any point during a trip where there may be obstructions that lower the number of satellites in view (e.g., tunnels, trees, buildings). These other types of problems are discussed in greater detail in the sections dealing with Applications 2 and 3.

To reformat and process the data, it is important to understand a number of aspects of GPS receivers such as the GeoLogger or the StepLogger. Firm software is included with most GPS receivers that not only calculates the position for each record, but also determines the content of some records and whether or not a record is output. In the Garmin GPS receiver attached to the GeoLogger, there are several built-in features that are important to know.

First, there is a predefined period of time that defines whether a new start in recording data is treated as a “warm start” or a “cold start”. In the equipment we have been using, a “warm start” is defined as re-starting collection of data within one hour of when the unit was last switched off, or stopped recording. In this case, the receiver assumes that it has not been moved from the last position recorded, and uses the last position as the assumed new position. Satellites are then searched for and “acquired” and recording of data usually commences within 15 to 40 seconds of powering the receiver. If the time since the receiver last recorded position is more than one hour (in our case), then the receiver firmware assumes that a new position must be established, and that the previous position cannot be assumed as the starting point. In this case, no recording of position takes place until at least four satellites have been acquired and position calculated. In this situation, the GPS receiver first needs to match the satellite signal with the receiver-generated code. After these two signals are matched, it also needs to collect the ephemeris of the satellites. (Normally, the GPS system updates the satellite ephemeris every two hours.) If the receiver is stationary while this process is taking place, then it may take 30-60 seconds for position to be acquired. However, if the receiver is already being moved, it may take as much as two to three minutes or longer for position to be determined, and has been found to take as much as fifteen minutes when the receiver is moving fairly rapidly (more than 60 km/h).

A second feature of most receiver firmware is that the receiver will interpolate position for some short period of time when the signal is lost or deteriorates. Therefore, when the satellite number is low, the HDOP is high, or under other conditions when position is not able to be known accurately, the receiver may provide latitude, longitude, altitude, heading, and speed by interpolation from the immediately preceding valid records. In most cases, this occurs for only very short periods of time, but means that those records may be unreliable.

There are a number of reformatting steps that are needed, together with creation of calculated values. Not all are required, depending on the receiver used. These are:

- Calculate local time and local date;
- Correct longitude for West/East;
- Remove the hemisphere designation for longitude;
- Correct latitude for North/South;
- Remove the hemisphere designation for latitude;
- Calculate the distance from the previous record, using the latitude and longitude;
- Calculate time in seconds based on zero seconds at midnight;
- Calculate elapsed time from the previous record; and
- Calculate actual date in date format and then calculate the weekday.

These steps are all fairly simple ones that could be programmed into almost any software capable of performing arithmetic calculations. Depending on the GIS software to be used, there may also be a need to rearrange data, and to provide a unique record number for each record in the data set. In this process, it is also generally desirable to begin removing invalid records. At this point, the reformatting becomes less than trivial.

In work at ITLS, the rules that have been applied are as follows:

- All data points with too few (less than three) satellites in view and/or a value of HDOP of five or greater are removed, except for each of the first occurrence of such data points in any group of data points of this type;

- Any data points where no movement is recorded are dropped, based on speed being zero, less than a 15 metre (0.00005°) change in either latitude or longitude, and heading also being zero or unchanged.

Speed will not always be shown as zero when no movement occurs, because the position accuracy of the GPS receiver attached to the GeoLogger and the antenna/receiver of the StepLogger is usually around  $\pm 10$  metres; therefore, the apparent position appears to move around, and some speed may be registered. However, in most instances, either or both the speed and the heading are zero, or the heading remains unchanged while speed is zero. If computations of elapsed time and distance from the previous record have been made, these need to be re-calculated after points are dropped, in order to correct for the missing data points and determine how long the GPS device was actually stationary.

### 2.1.2 Trip Detection Algorithm

Because the collection of data by GPS devices has the potential to provide very large quantities of data, it is necessary to develop automated procedures to analyse the data, and convert it to readily visualised information for respondents, analysts, and decision makers. The need is for some rule-based algorithms that can do the following:

- Detect a trip end when the ignition has been turned off (in-vehicle device only);
- Detect a trip end when the ignition has not been turned off (in-vehicle device only);
- Detect a trip end from wearable data, where the device is always on;
- Detect a trip end that occurs when direction is reversed, but there is a very short or non-detectable stop;
- Determine whether a trip ended and a new one started during a period of signal loss in the middle of what appears to be one trip; and
- Determine whether there is a loss of signal at the beginning of a trip and repair the data record if there is.

The first of these is relatively trivial, but occurs only with in-vehicle devices, powered through the car's accessory slot. If the ignition is turned off for a period of time, the first record after the ignition is turned on will have a large elapsed time from the previous record, as shown in Figure 3. Because of cold start problems, this will also often be followed by a series of data points with zero speeds, indicating that correct position has not yet been re-established. In Figure 3, it can be seen that the GPS device was turned off for a period of approximately 78 minutes, after which, it took just over one minute to acquire position, or the vehicle was stationary for one minute, before moving off.

We experimented and found a rule that worked well to detect trip ends. If there was 120 seconds or more of elapsed time between two successive in-motion data points a trip end was assumed to have occurred. (In survey work in which this has been used, it appears that this rule results in detection of a few fictitious trip ends. In our surveys, approximately three percent of the trip ends identified turned out not to be valid trip ends.) Such locations are found by removing any data points where the movement between successive data points is less than the accuracy rating of the GPS device. In our case, the GPS devices in use are rated to have an accuracy of within  $\pm 10$  metres. However, when stationary, the position rarely changes by more than a few metres, with a speed of 0.0 km/h, or nearly so. Therefore, by removing those points where the speed is shown to be zero, and there is little change in position, we can detect when there is a stop lasting two minutes or longer, and define that as a probable trip end. Again, by inspection of known short stops, we found that setting a limit on the change of latitude or longitude to 15 metres (0.00005°), which represents a distance of movement of less than 7 metres, we could be fairly certain of detecting a stop. It is worth noting that most traffic signals in Australia at least have a red-light cycle of less than two minutes.

**Figure 3:** Partially Manipulated Data Showing a Trip End

ID	LONGITUDE	LATITUDE		Actual Time	Actual Date	Day	Speed kph	Time in Seconds	Elapsed Time	Distance (m)
485	151.276200	-33.741083	154448	15:44:48	26-Jun-01	3 Tuesday	4.17	56688.0	5.00	5.8
486	151.276100	-33.741133	154453	15:44:53	26-Jun-01	3 Tuesday	9.00	56693.0	5.00	12.5
487	151.275967	-33.741183	154458	15:44:58	26-Jun-01	3 Tuesday	0.00	56698.0	5.00	0.0
488	151.275950	-33.741200	154503	15:45:03	26-Jun-01	3 Tuesday	4.17	56703.0	5.00	5.8
489	151.276000	-33.741200	170332	17:03:32	26-Jun-01	3 Tuesday	0.00	61412.0	4709.00	0.0
490	151.276000	-33.741183	170337	17:03:37	26-Jun-01	3 Tuesday	0.00	61417.0	5.00	0.0
491	151.275983	-33.741167	170342	17:03:42	26-Jun-01	3 Tuesday	0.00	61422.0	5.00	0.0
492	151.276000	-33.741150	170347	17:03:47	26-Jun-01	3 Tuesday	0.00	61427.0	5.00	0.0
493	151.276000	-33.741150	170352	17:03:52	26-Jun-01	3 Tuesday	0.00	61432.0	5.00	0.0
494	151.276000	-33.741150	170357	17:03:57	26-Jun-01	3 Tuesday	0.00	61437.0	5.00	0.0
495	151.276000	-33.741167	170402	17:04:02	26-Jun-01	3 Tuesday	0.00	61442.0	5.00	0.0
496	151.276000	-33.741167	170407	17:04:07	26-Jun-01	3 Tuesday	0.00	61447.0	5.00	0.0
497	151.276000	-33.741183	170412	17:04:12	26-Jun-01	3 Tuesday	0.00	61452.0	5.00	0.0
498	151.276000	-33.741183	170417	17:04:17	26-Jun-01	3 Tuesday	0.00	61457.0	5.00	0.0
499	151.276000	-33.741183	170422	17:04:22	26-Jun-01	3 Tuesday	0.00	61462.0	5.00	0.0
500	151.276000	-33.741183	170428	17:04:28	26-Jun-01	3 Tuesday	0.00	61468.0	6.00	0.0
501	151.276017	-33.741183	170433	17:04:33	26-Jun-01	3 Tuesday	0.00	61473.0	5.00	0.0
502	151.276100	-33.741133	170438	17:04:38	26-Jun-01	3 Tuesday	1.67	61478.0	5.00	2.3
503	151.276200	-33.741117	170443	17:04:43	26-Jun-01	3 Tuesday	3.17	61483.0	5.00	4.4
504	151.276250	-33.741067	170448	17:04:48	26-Jun-01	3 Tuesday	3.17	61488.0	5.00	4.4
505	151.276500	-33.741067	170453	17:04:53	26-Jun-01	3 Tuesday	24.83	61493.0	5.00	34.5
506	151.276800	-33.741100	170458	17:04:58	26-Jun-01	3 Tuesday	15.50	61498.0	5.00	21.5
507	151.276917	-33.740933	170503	17:05:03	26-Jun-01	3 Tuesday	28.83	61503.0	5.00	40.0
508	151.276983	-33.740467	170508	17:05:08	26-Jun-01	3 Tuesday	37.33	61508.0	5.00	51.9

In summary, we flag a trip end if:

- The difference in successive latitude and longitude values is less than 0.000051 degrees AND
- The heading is unchanged or is zero AND
- Speed is zero AND
- Elapsed time during which these conditions hold is equal to or greater than 120 seconds.

If there is a break in the record, meaning that the engine was turned off, for between 30 and 120 seconds, this is also defined as a potential trip end. However, for these situations, a flag is set for subsequent manual inspection of these records, to determine whether a trip end is really apparent.

The third situation that is automatically detected is when the vehicle reverses direction. Reversal is defined as having occurred if the heading changes within 30 seconds by between 178 and 182 degrees. Such occurrences also may arise when a driver realises that he or she has taken a wrong turning, or missed a turning, and reverses to find the correct location. It also may occur on a divided highway, where a driver needs to make a U-turn in order to reach an address on the other side of the street. In this case, the trip is likely to end shortly after the U-turn. However, it is unlikely that any rule-based algorithm will be able to detect and differentiate this from a situation in which a driver serves a passenger, or performs some other activity and immediately reverses direction.

The wearable version of the GeoLogger performs in the same way as the in-vehicle version with the exception that it was powered by a portable battery source rather than the cigarette lighter of a vehicle. Therefore the same procedure was employed for the detection of trip ends without the use of the device being turned on or off by the ignition of a vehicle. Because

the wearable devices are able to be carried in-doors, a trip-end is able to be identified in the same manner as if it had been turned off for 120 seconds or more. When the GeoLogger is taken in-doors, the satellite signal is lost and hence there are no data points recorded. When the GeoLogger is taken outside again and a position is “acquired”, data points are again recorded. Our program recognises that this is more than 120 seconds than when a signal was last lost and identifies this as the start of a new trip.

The StepLogger also performs in a similar manner. The one notable difference is that, to our specifications, zero speeds are not recorded. The rationale is that it substantially reduces the number of “useless” data records. These occur when the StepLogger may be left somewhere where it can still record position (i.e., outdoors), but is not in motion for extended periods. An example of this would be if the device was left in the car all day while somebody was at work. The output of a situation such as this would be thousands of records in the same position. This would also exhaust the memory capabilities considerably. These data records are generally not useful for the purposes of travel surveys.

The omission of zero records and the nature of GPS measurement errors lead to the necessity of a further rule to be created. Speed is calculated from change in longitude and latitude. When a device is stationary, the GPS measurements will jump about slightly (within a few metres of each other). These two points mean that a speed is being calculated whenever the measured position changes – generally at 1km/hr. Therefore, despite zero speeds being removed and the device being stationary, there are still erroneous records of 1km/hr. Hence a trip-end is not recorded when it should be. To account for this, a rule was developed where if a group of records are within 30 metres of each other they are grouped into what is called a “StopPointSet”. However, all records within this group of records must be within 30 metres of each other, i.e., no record within a StopPointSet may be 30 or more metres apart from another. Once a record is 30 metres or more apart from a previous record, it is this previous record that is considered as the point of reference for a trip-end, (as long as this point of reference and the record that is 30 or more metres apart are two or more minutes apart). The record that is 30 metres from the point of reference is the first record of the next trip. The rationale for using 30 metres stems from previous analysis of data records of stationary devices. It was found that the accuracy lay within 10 metres and therefore, using three times the standard deviations (30 metres), as the critical range to determine when the GPS device starts to move again provides 97% confidence.

At this point, the continuous GPS record has been manipulated, so that the different attributes are transformed into more usable values, the data have been rearranged, if necessary, to fit the input requirements of the GIS software, records that represent no movement are deleted (except for the first record at the beginning of each period of no movement), and the records have been divided into groups that appear to represent a trip. In our procedures, at this point, we also attach a trip number to each record, starting the count with each new day in the record, and we also attach a sequence number to the records in each trip, with the first record at the beginning of the trip being numbered 1, and subsequent records being consecutively numbered up to the end of the trip.

## **2.2 Application 2: Correction of Cold Start Problems**

The “warm start”/“cold start” problem causes several analysis problems. First, very short trips may be lost completely, because position is never acquired during the trip. This is particularly the case for movements of a vehicle over a distance of one or two kilometres and for short walks with a wearable GPS, where a “cold start” receiver may not record position. Second, when the trip is long enough for position to be acquired, the resulting trip will be shown to be shorter in length and duration than the real trip. Third, in providing information to survey respondents in a prompted recall survey, the missing trip start information is troublesome, because it does not correspond with what the person actually did.

The following describes our approach to the receiver warm up problem, and our methods for interpolating time and distance for the initial part of a trip where no position is acquired. The reason for doing this is to be able to provide a better estimate of when the travel began, and to correct the trip length in both distance and time from the GPS device. This is important if the GPS device is being used to estimate emissions, or when presenting the data in a prompted recall survey, so that respondents are presented with more accurate data. It is also very important when being used as a measure of vehicle kilometres travelled (VKT). If signal acquisition occurs within 100 metres of the real origin of the trip, this is generally not a problem. However, when distances exceed 100 metres, both the time and distance information from the trip may appear incorrect when compared to another trip between the same two geographic locations.

### 2.2.1 Diagnosis of In-Vehicle Cold Start Problems

This is a sub-routine procedure that requires the following information:

1. The distance between the start of the trip and the end of the previous trip.
2. The location of the start of the trip to see if it starts in **Zone I** or **Zone II**.
3. The location of the end of the previous trip to see if it ends in **Zone I** or **Zone II**.
4. If the distance is between 12 and 2050 meters, inclusive, then this program is run to fix the trip gap.

**Zone I** is the Sydney CBD and surrounding area while **Zone II** is the rest of the Sydney metropolitan area. The following steps are undertaken in the Trip Connection program: First, a proposed average speed is set up for Zone I and Zone II for different gap distance ranges. These are defined in Table 1. We compute the average speed of the last 10 records of the previous trip. If the number of records is less than 10, then we take all records and compute the average speed. (Note: the speed is calculated speed; it is not the speed recorded by the GPS device.)

Second, we determine the speed for the gap. This is done in two ways, one for Zone I and one for Zone II. If both trips are in Zone II, then the speed for the gap will equal to the proposed average speed for Zone II depending on the gap distance. If either of the trips is in Zone I, then the speed for the gap will equal the proposed average speed for Zone I, based on the gap distance, except for the 12 to 150 meters range. For the 12 to 150 meters distance range, if the distance between the first and the second GPS record of the trip is less than 100 meters and the total number of records of the previous trip (maximum 10 records) and the current trip (maximum 10 records) is not less than 13, then the speed for the gap will be the average speed of those records (maximum 20 records in total), otherwise, the speed for the gap will be kept as equal to the proposed average speed for Zone I.

Third, we determine the distance for the gap. The first case is when both trips are in Zone II. In this case, if the straight line distance between the start and end record of the two trips is between 12 and 100 meters, then the gap distance will be equal to this distance. However, if the straight line distance between the start and end record of the two trips is between 100 and 300 meters, then the gap distance will be the length of the shortest path between the two nodes, of which one is the nearest node to the end of the GPS record of the previous trip and the other is the nearest node to the start of the GPS record of the current trip. If the straight line distance between the start and end record of the two trips is between 300 and 2050 meters, then the gap distance will be the sum of the length of the shortest path between the two nodes, defined as before, and the distances between these two nodes and their corresponding GPS records.



**Table 1:** Average Speeds for Zone I and Zone II, Based on Length of the Gap

Between (excluded, meter)	To (included, meter)	Average Speed for Zone I (km/hr)	Average Speed for Zone II (km/hr)
12	150	18.44	21.39
150	250	19.98	24.73
250	350	20.56	27.11
350	450	20.76	29.62
450	550	20.81	30.74
550	650	21.57	31.95
650	750	21.83	33.47
750	850	22.35	33.69
850	950	22.17	33.65
950	1050	22.35	34.87
1050	1150	22.78	35.03
1150	1250	22.52	35.34
1250	1350	22.72	35.85
1350	1450	22.74	35.88
1450	1550	23.23	36.53
1550	1650	23.97	36.84
1650	1750	23.81	37.10
1750	1850	24.42	37.71
1850	1950	24.60	37.83
1950	2050	24.48	38.31

The second case is when either of the trip ends is in Zone I. In this case, if the distance between the start and end record of the two trips is between 12 and 300 meters, then the gap distance will be equal to this distance. If the distance between the start and end record of the two trips is between 300 and 2050 meters, then the gap distance will be sum of the length of the shortest path between the two nodes, defined as for the first situation, and the distances between these two nodes and their corresponding GPS records.

Having established this distance, we then compute the travel time for the gap based on the speed and distance for the gap in previous steps. We also compute the time for the trip connection by adding up the travel time for the gap and appropriate terminal time (13.6 sec for Zone I and 20.2 sec for Zone II).

### 2.2.2 Correction of Other Cold Start Problems

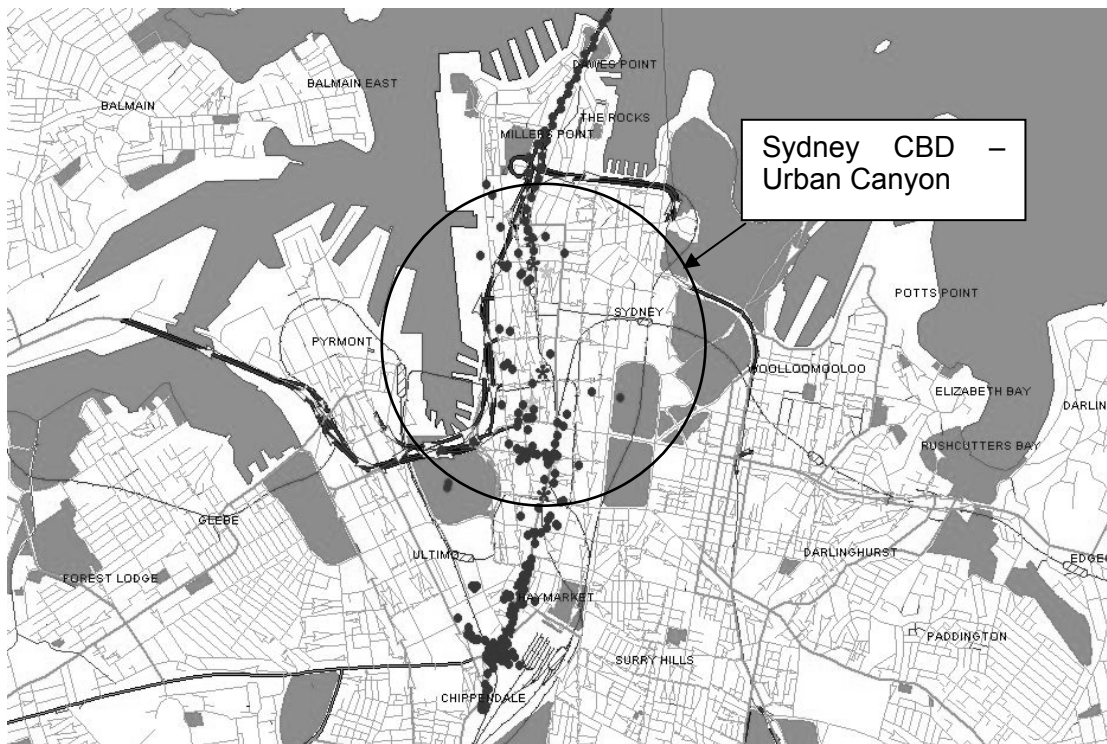
While the above procedure works well for loss of data points in a car, it does not assist in repairing data obtained from walking, bicycling, or riding in public transport vehicles. Also, if the trip before the cold start and the trip following the cold start are on different modes, then nothing can be learned about speeds of the missing data from the data immediately before the cold start and the data immediately after recording begins again. These are problems on which we are still working, because we are still accumulating wearable device data to inform the process.

## 2.3 Application 3: Correcting for Signal Loss in “Urban Canyons” and Under Other Circumstances

Another problem that affects GPS receivers is signal loss when travelling along a roadway between tall buildings. In effect, this limits the view of the sky for the GPS receiver to a strip that is directly overhead. This will normally result in there being less than four satellites in view, and also in the HDOP reaching a high number. As a result, reliable position information is not obtained. Similar results arise when the vehicle that is equipped with the GPS enters a tunnel, or travels along a roadway with a heavy tree canopy, and also occurs when the user of a wearable device boards a public transport vehicle. In general, when situations of this type arise, there are good records up to the point where the canyon, tunnel, or public

transport vehicle is entered, and there are good data points again, after the vehicle emerges from the canyon or tunnel, or when the person disembarks from the public transport vehicle.

The issue here is twofold. First, if signal loss was caused by buildings or foliage, has a stop occurred in the obscured area, which would be impossible to detect, given the missing and unreliable points? An illustration of the type of data received is shown in Figure 4. Second, the route taken through the area is not known in most cases. However, if it is a tunnel, then there will not be places (usually) where a stop could have been made and the route would be known. This is the least difficult situation. If it is a city centre area, then the routing will not be known, and a direct or minimum time/distance path will not always be appropriate. Nevertheless, for the purposes of playing back the data to respondents, finding a minimum path is sufficient to use in a prompted recall survey and also provides reasonable accuracy for most other purposes. In the event that signal loss occurs because of riding on a public transport vehicle, it will be evident where the person boarded and where they alighted, and the route will usually be evident. In fact, in most instances, we find that the signal is regained once the person alights from public transport, unless this takes place in a tunnel or other sheltered location.



**Figure 4: Scatter of Points Resulting From Urban Canyon**

It is possible to overcome these problems with more advanced GPS equipment. One option would be to use GPS in combination with a dead reckoning based positioning system. Dead reckoning is the process of determining position by projecting course and speed from a known past position (Wood and Mace, 2001). These systems generally use some type of solid state gyro to calculate speed and heading to determine a differential position which can be used to continue navigation until satellites can be reacquired. Unfortunately such equipment is considerably more expensive (and less portable) than that currently used at ITLS. At this point in time, we are not aware of any low cost, portable GPS data loggers that incorporate these features. However, it is likely that such technology will be available in the not too distant future. There are also possibilities to combine GPS positioning with cellular phone positioning, which although less accurate, may provide position information in locations where GPS is unavailable.

Currently, the problem must be corrected in the post processing phase. This again requires that there is an underlying GIS layer on which there is a complete street network, which can be used to find a minimum path. The principle of the correction process is as follows. First, it is determined if the travel is taking place on public transport. This is determined by correlating the last point of recording with a known public transport route (and possibly either a bus stop or train station location), and also determining that the next data points recorded are either in walk mode, or indicate a location of another bus stop or train station. (In Sydney, we also add ferry terminals to this.) In the event that we have determined that the missing trip segment is on public transport, then the route is taken from the underlying GIS layer that represents the appropriate travel means. The distance is determined from both the GIS and the change in latitude and longitude from the point of boarding to the point of alighting, while the time is determined from the GPS record. If it is now determined that the trip is by car, then a different procedure is used.

For car, first, the entry and exit points are identified. The ten records preceding the entry and the ten records following the exit are taken and average speeds are computed from these records. If there are fewer than ten records available either before the entry or after the exit from the obscured area, then all records available at the ends of the trip are used. Again, however, if there are fewer than 13 records in total, then a look-up table of speeds is used. The minimum path through the network is determined from the entry and exit points and the underlying street network. The distance of this path is determined. The elapsed time between entry to the obscured area and exit from it is also calculated.

Using the distance from the minimum path, the implied speed is determined for the missed segment of travel. Because urban canyons are often in areas where there is significant congestion, it can be expected that speeds will be lower through the urban canyon than before entry into it and departure from it. Even if there is an absence of congestion in the area, entry and exit speeds are still likely to be higher because major access roads into and out of urban canyons are, in most cases, designed to move large volumes of traffic relatively quickly (e.g., by freeways or through signal priority). The rule is that if the implied speed is less than 50 percent of the speed determined from either the 20 points on either side of the urban canyon, or than the look-up speed, then a stop is assumed to have occurred in the obscured area. If the speed is greater than or equal to 50 percent of the speed from the 20 points or the look-up table, then no stop is assumed, and the points of entry and exit are joined, using the minimum path.

## **2.4 Application 4: Displaying the Data**

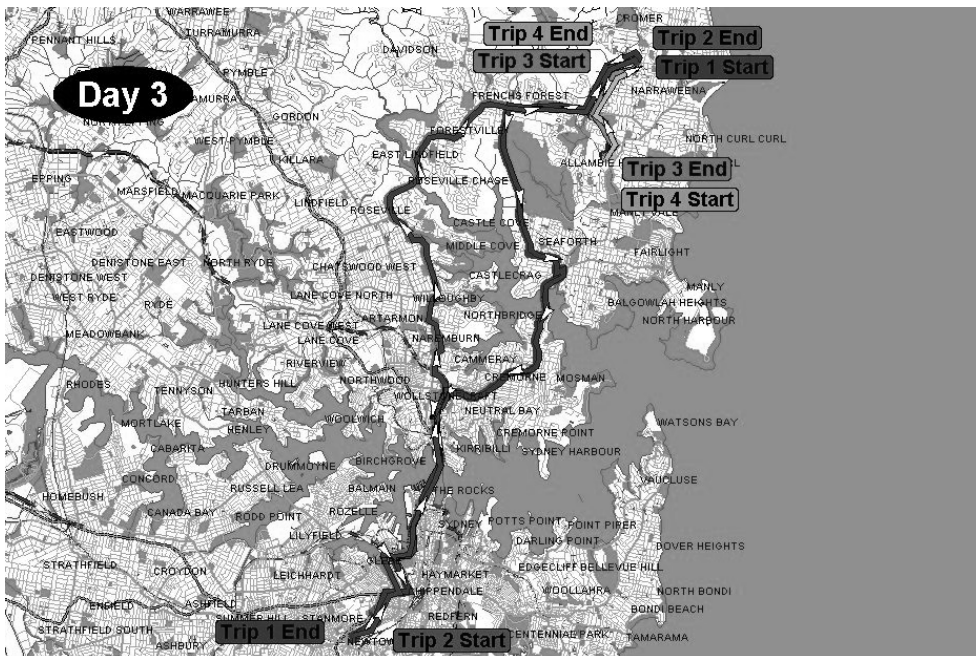
Once all of the above three steps have been completed (conversion to trip-based records, correction of cold start problems, and corrections for canyon effects), a geographic file is created for each day's records, with the trips within the day being colour coded, so that all of one day's trips from one device can be displayed on a map. This fourth application is not described in full in this paper as the primary use is for prompted recall surveys. It is still useful for in-house manual checks and therefore a quick overview of the displaying capabilities is given.

Starting with these daily geographic trip files, each trip is displayed as a solid line, corresponding to the underlying road or route system. The coloured trip lines are also annotated with directional arrows, to show the direction of movement at all points along the trip. Each trip-end is labelled with at least a trip number, and also potentially the location, when it is known (e.g., home, workplace 1, etc.). Finally, because not all respondents are comfortable with maps, it is desirable to be able to provide a printed summary of the trips that could be used as an alternative prompt in the survey. A database file is created. This contains the start and end times of each trip, any tolls incurred (determined from passage through a GIS-encoded toll gate), etc, the elapsed time and distance for each trip and locality information including the street name, suburb name, postcode, latitude and longitude. The

average speed for each trip is also given. For purposes of prompted recalls, a summary table is produced. This shows the start and end location of each trip in words, the time at which the trip began and ended, the length of the trip in distance and time, tolls incurred, and the average speed. Each map is labelled for the day on which the travel took place. The procedure is repeated to create a map for each day for which observations were obtained. Figure 5 shows an initial plot of the GPS records as a point layer, and Figure 6 shows the results of all correction and visualisation procedures.



**Figure 5: Initial Plot (Colour-Coded) of GPS Points for One Day's Travel**



**Figure 6: Processed Data to Continuous Lines Representing Trips**

### 3 Determining Mode and Purpose

#### 3.1 Mode

Our method for determining the mode of travel works on a process of elimination. It is easiest to define walking trips, because, in most urban areas, these are markedly slower than any other mode of travel. Most people walk at between 4 and 6 km/h, and speeds this low are not usually maintained on any vehicular mode. Therefore, the first step is to isolate trips that have been defined in the earlier steps, where the average speed is not greater than 6 km/h and the maximum speed is not greater than 10 km/h. A further identification for these trips will be that they will not necessarily follow the street layer of the GIS, especially in areas such as parks and open spaces.

The next in order to be identified are trips by public transport. Usually, these will be preceded by, followed by, or fall between walk trips. They will have two other characteristics. The beginning and possibly the end should be on a public transport line, and there may be evidence of periodic stops that do not necessarily coincide with intersections, if the device was able to retain position while in use on a bus. (In Australia, most bus stops are midway along blocks, and do not occur at intersections.) In the event that there is an apparent end to a walk trip, and then the respondent “reappears” some distance away from the starting point, we compute the average speed. If this is in the range from 10-40 km/hr, the trip is probably a bus trip. If it is a higher speed and the starting and/or ending point is on a rail line, then the trip is probably a rail trip. There is also the case of the O-bahn and the Glenelg Tram in Adelaide, which are easily recognisable from the network layer, provided that points are recorded along the line.

Our experience is that recording of position is sporadic in buses, non-existent in trains, and usually good, if not complete, by car and bicycle. At this point, any remaining trips that have not been assigned a mode should be either car or bicycle and should have fairly continuous recording of position. A further check of speed is all that is required, generally, to distinguish the two. An average speed of less than 40 km/h, except in areas of known prolonged congestion, will normally be associated with bicycle. Car will usually average above 40 km/h. In addition, car trips will normally run along the streets of the GIS street layer, while bicycles may deviate from the street network, especially in areas with cycle paths. However, one further check is to see if the entire trip runs along a bus route. In this case, there is a possibility that the recorded trip is a bus trip, and further investigation, such as for periodic stops that do not coincide with intersections, will be necessary to determine the mode.

We find that this method identifies mode correctly about 95 percent of the time. The biggest problems occur where the GPS record is patchy and there is insufficient evidence to permit us to be sure of the mode. This can be particularly true of bus trips, which may sometimes be indistinguishable from a car trip that has poor GPS reception, or a car trip that takes place under congested conditions.

#### 3.2 Purpose

To ascertain trip purpose involves some initial data collection at the time of recruitment. This involves ascertaining the addresses of each person’s workplace or school, and the address of the two most frequently used grocery stores. It is also only feasible to conduct where there is a detailed and reasonably accurate land use map available in GIS. Knowing the home address, the addresses of each worker’s workplace (we usually collect up to two workplaces per worker) and the address of the educational establishment for those in full-time or part-time study, together with two grocery stores, provides data that will usually identify about 75 percent of trip ends and yield trip purposes for well over 60 percent of trips, without further

information. For the remainder, it is necessary to categorise the land uses and then deduce the probable purpose from it, using a set of heuristic rules. We also collect information on occupation, and this is one additional item that is sometimes needed to help identify the purpose at each trip end.

It is also important to specify the level of detail desired in trip purpose categorisation. For applications where we need trip purpose, we have determined currently that the purposes required are:

1. Home-based work
2. Home-based education
3. Home-based shopping
4. Home-based eat meal
5. Home-based personal/medical
6. Home-based social/recreational
7. Home-based pick-up/drop-off
8. Home-based other
9. Non-home-based work-other
10. Non-home-based other-other

Home-based work (1) is easiest to identify, except for persons who do not have a fixed workplace. For all others, these trips fall out of the address information collected at the recruitment stage. Generally, these trips account for about 10 percent of a household's trips. Similarly, home-based education trips (2) also are easy to identify for those who are engaged in full-time or part-time education. These trips account for about a further 6 percent of trips. Most home-based shopping trips (3) can be identified from the address information provided, although others will be identified from trips that are made to other retail locations. However, if the person's occupation is in retail, and the workplace is a retail store, this will always be classified as work. Trips made from retail to retail will be classified as purpose 10, while those between home and retail will be classified as purpose 3. Trips between work and retail will be classified as purpose 9, and we generally do not need to know if this is work-related or not. These trips will usually account for about another 10 percent of total trips.

The next step in the process is to isolate those trips that go to a residential land use, other than the person's home. With the exception of occupations that involve house calls, such as plumbers, garden maintenance workers, and other similar occupations, visits to a residential address would be categorised as social-recreational trips. For persons indicating an occupation that would involve visiting residential addresses, and provided that, in most cases, the trips take place in normal working hours, these trips would be classified as either home-work trips or work-work trips, i.e., purposes 1 or 8. Trips to commercial land uses, such as finance, insurance, real estate, banking, post office, etc. would be categorised as personal business (purpose 5). Trips to medical and health facilities would be categorised as medical care trips (purpose 5), although trips to a hospital, with a relatively short duration (up to one hour) would be categorised as social-recreational (purpose 6), while visits of longer duration would be assumed to be for a medical purpose (purpose 5). Trips to a gym, swimming pool, park, or other exercise-related location would be categorised as personal business. Trips by a person not in education to an educational establishment would be categorised as pick-up/drop-off (purpose 7) if the duration at that location is less than 15 minutes, and as personal business if the time is longer than 15 minutes. Trips to restaurants, fast food locations, cafes, etc. would be categorised as eat-meal (purpose 4).

All trips that have an origin and a destination, neither of which is home or work, are categorised as other-other (purpose 10). Trips that have one end at work and the other at some other location are categorised as work-other (purpose 9). Trips with one end at home and the other end at any other type of land use than those discussed here, are categorised as home-based other trips (purpose 8).

All trips can thus be categorised. Some errors are always likely to occur in a set of heuristic rules of this type. However, we believe that, for most transport planning related purposes, this categorisation is adequate and sufficiently accurate.

## **4 Data Management and Storage**

GPS data loggers provide one simple comma delimited file, but this quickly expands into hundreds, maybe even thousands of files when processed and analysed in GIS. Consider the example of a GPS device fitted in the vehicle of a single person household for five days. Set on a polling rate of 5 seconds, the device recorded a total of 22 trips over the five day period. While the CSV output file from the GeoLogger was only 353 KB, around 350 data files, totalling 10 MB, were produced from the trip processing application.

Data management is therefore a critical issue in GPS research. Even projects of a moderate scale can produce massive quantities of data. Managing the myriad files that result is key to being able to make maximum use of the data. In the following subsection, we describe the procedures that we are now using, based on the GIS software and the special application programs we have developed.

In the procedures described in this paper, the CSV file is imported directly into TransCAD. All processing is then done automatically in one application, with specification of file names, directories and so forth being performed from dialogue boxes that appear during the processing. Geographic files are created for each day of travel, which reduces the number of files from having a separate file for each trip. Different colour styles are automatically applied to each trip within a day. In the case that a prompted recall survey is being conducted, the conversion procedure from a point layer to a line layer is performed automatically in the software. A summary table is also generated automatically for each day's worth of trips, and no manual inputs are required to the table. Maps are also produced automatically for each day, with labelling of trip ends and trips, colour coding of trips, and directional arrows. The files produced by the program are reorganised so that all files from one device are saved in the same folder as the csv file except the map file. The map file is saved in a separate location to make it easily accessible for printing or displaying.

All of the above procedures can now be completed in a period of about two hours or less for each GPS device with five to seven days of data. In addition, skilled operators are not required for the data processing (whereas the original procedure required the use of individuals who had skills in the GIS software and in SPSS). There is the potential to output data at an intermediate point for examination of the trip ends, and determination if some spurious trip ends might have been identified. This step may add an hour or so to the processing time.

## **5 Conclusion**

While collection of GPS data has become considerably easier over the past few years, and it is now possible to collect large quantities of GPS data on personal travel, vehicular travel, etc., the amount of data that may need to be managed and manipulated is larger than many professionals realise. As a result of this enormous quantity of data, it is necessary to develop procedures for managing and manipulating the data, so that useful information can be provided, and so that ready access can be provided to the resulting files.

In this paper, we have described a series of procedures that have been developed to manipulate data collected from GPS devices carried by people or placed in personal vehicles, and used to produce records of the trips made over a period of days or weeks. By setting up various algorithms and rules, we have found it to be possible to break the data up

into trips with approximately a 95 percent correct rating in identifying real trips. We have developed procedures to correct some of the major potential problems encountered in using GPS devices, such as the cold start problem and urban canyons. Our procedures in these two cases have been found to provide a high degree of accuracy in completing partial records from GPS devices. As a result, we are able to obtain a more complete picture of where a person/vehicle travelled while they had the GPS device.

Finally, we have developed procedures that allow us to impute the mode and purpose of the majority of the recorded trips. This procedure has allowed us to analyse the data without the need to undertake further questioning of respondents, thereby providing this as a low burden method of data collection.

The automation that has been permitted by programming these rules has not only been effective in managing the data and providing ready information to those who may need to review the data. The automation has also provided a potential reduction in the level of time and effort required to process data on the order of a reduction to 20 to 25 percent of the amounts of time required for a manually-assisted procedure.

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